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# MAPPING THE ROUGHNESS PARAMETERS IN A LARGE URBAN AREA FOR URBAN CLIMATE APPLICATIONS

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**Összefoglalás** – A munkánk fő célja egy városi felszín érdesség térképezési eljárás bemutatása egy nagy szegedi vizsgálati területen. Ezzel a térképezési eljárással képesek vagyunk a ventilációs folyosók lehatárolására a városok területén. A feltételezett ventilációs folyosók fontos szerepet játszhatnak a városi hősziget cirkuláció kifejlődésében, ezáltal a légtér szennyezettségének csökkenését eredményezve a város központi részein. Ezek az eredmények fontos alapadatokat szolgáltathatnak a várostervezési munkákhoz. Eredményeink alapján lehatárolhatjuk azon területeket, amelyeknél a városvezetésnek célszerű lenne megőrizni a ventilációs folyosók humán komfort szempontból kedvező hatását a városklímára. Az érdességi paraméter számításaink 3D épület adatbázison alapulnak és részletesebbek, mint a legutóbbi hasonló munkák (e.g. *Bottema*, 1997; *Ratti et al*, 2006). Számításunk úgynevezett *lot area* poligonokon alapul, amely az általunk ismert publikációk alapján példanélküli megközelítés.

**Summary** – The overall purpose of this study is the presentation of an urban roughness mapping method in a large study area in Szeged. With this roughness mapping procedure we can locate the ventilation paths in the city. The supposed ventilation paths could play a significant role in the development of the urban heat island circulation and as a result in the reduction of air pollution in the inner part of the city. These results could provide important input data for urban planning procedures. Based on our results we can give a list of the areas where the city government should keep the advantages of the ventilation paths considering the human comfort aspects of the urban climate. The calculations of the roughness parameters are based on a 3D building database and they are more detailed than in other recent studies (e.g. *Bottema*, 1997; *Ratti et al*, 2006). Our calculation based on the lot area polygons is a new approach and according to our knowledge there are no similar examples in the literature.

*Key words*: urban roughness mapping, frontal area, roughness length, porosity, Szeged, Hungary

## 1. INTRODUCTION

In the settlements the primary geometry and surface characteristics have been changed compared to the original natural surfaces. Urban environments modify the water and energy balance which often results in higher urban temperature compared to the relatively natural surroundings (urban heat island – UHI). The effect of the urban surface on the air flow is also one of the most important differences.

The cities are about the roughest surfaces. Because of the roughness of the surface, wind speed decreases in urban areas. The average wind speed is lower in the cities than in rural areas (*Oke*, 1987).

In direct analogy with the well-known sea breeze system the cities generate a local air flow the so-called country breeze, which is based on the fact that the cities are commonly warmer than the rural background. For the development of the country breeze the regional winds need to be very weak, so anticyclonal weather conditions are ideal for this flow system. This includes low-level breezes across the perimeter, which converge in the center. The vertical thermal differences are as important as the rural urban thermal differences (*Oke,* 1987). The vertical instability and the different heating distributions induce this 3 dimensional weak circulation (*Vukovich,* 1971). There is uplift in the centre of the city and there is also a counter-flow in the higher air layer (*Fig. 1*). Unlike in the case of the sea breeze there is no diurnal reversal because the city is usually warmer than the countryside. During the day the small horizontal thermal gradient is sufficient to drive this system. Due to the larger roughness of the surface the average wind speed is lower in the cities than in rural areas (*Oke,* 1987).

Owing to the high surface roughness of the city the development of the country breeze needs significant thermal difference between the urban and rural surface. During the day the country breeze can be observed above the roof level. At night the thermal difference is significant under the roof level therefore the country breeze can be found here. In summary, this is the urban heat island (-induced) circulation (UHIC) (*Eliasson and Holmer,* 1990).

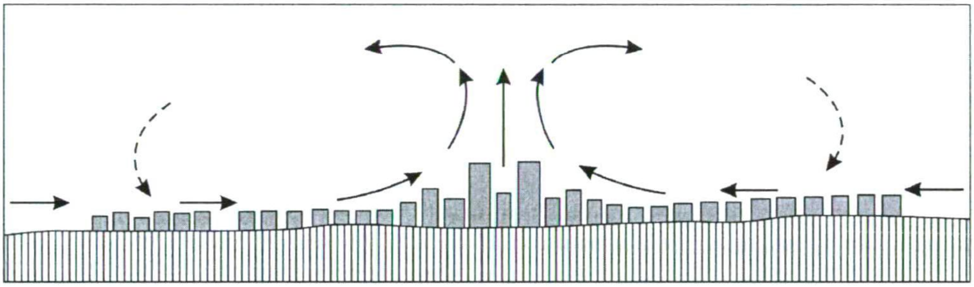

*Fig. 1* The schematic shape of the urban heat island circulation

This meso-scale circulation could offer a potential for the improvement of the urban air quality (*Barlag and Kuttler,* 1990). The depth of the inflow in the UHIC system depends on the roughness of the surface. In the ventilation paths – where the roughness is lower than in other urban areas – the country breeze can reach the inner parts of the city and it decreases the pollution accumulated during the day.

For describing the roughness of the surfaces numerous parameters are known. The prevalent parameters are the zero-plane displacement height ($z_d$) and the roughness length ($z_0$) (*Lettau,* 1969; *Counihan,* 1975). Further known parameters are the plan area density ($\lambda_p$), frontal area density ($\lambda_f$), average height weighted with frontal area ($z_H$), depth of the roughness sublayer ($z_r$) (e.g. *Kutzbach,* 1961; *Raupach,* 1992; *Bottema,* 1997; *Grimmond and Oke,* 1999) and the effective height ($h_{eff}$) (*Matzarakis and Mayer,* 1992). The porosity of the urban canopy layer ($P$) can also be a useful tool for urban roughness mapping.

If we evaluate the roughness parameters in a large urban area we have the opportunity to find the potential ventilation paths which are essential for enhancing the efficiency of the country breeze. *Matzarakis and Mayer* (1992) summarize the main properties of the ventilation paths with the following points: a) aerodynamic surface roughness length lower than 0.5 m, b) negligible zero point displacement, c) sufficiently great length in one direction, at least 1000 m, d) sufficiently great width, minimum width is double to four times the height of the lateral obstacles, but et least 50 m, e) the edges of ventilation paths should be comparatively smooth, f) the width of the obstacles in a ventilation path should not be greater than 10% of the width of the ventilation path, g) the height of the obstacle in a ventilation path should not be greater then 10 m, h) obstacles within a ventilation path should be oriented in such a way that their greatest width is parallel to the axis of the ventilation path, i) single obstacles within a ventilation path should have a ratio of height to horizontal distance between two successive obstacles of 0.1 for buildings and 0.2 for trees.

Based on these results there is an opportunity to give some advice for the local government on how to promote the intrusion of the cool and clean air and to decrease urban air pollution. *Barlag and Kuttler* (1990) summarized these advices in six points:

(a) almost straight free aisles must be kept to the centre of the city;

(b) surface roughness along these free aisles must be kept low;

(c) ventilation aisles into city centers must feature low-roughness vegetation to filter out pollution;

(d) surfaces in these areas should have a cooling effect on the 'thin-layered' air moving slowly towards the centre of the city;

(e) clearances to take air into the city centre should be designed to give directional stability to air flows;

(f) pollution should be minimized in the areas from which air moves to the city centre and along the ventilation aisles.

The overall purpose of this study is the presentation of an urban roughness mapping method in a large study area in Szeged. The specific objectives are (i) to describe the application of the roughness length calculation method in irregular building groups, (ii) to present the calculation of porosity in the urban canopy layer, and (iii) to find the potential ventilation paths in the study area using the calculated urban roughness parameters.

## 2. METHODS FOR THE DETERMINATION OF ROUGHNESS PARAMETERS

There are numerous ways for the $z_0$ and $z_d$ calculation. There are two classes of these methods: (i) micrometeorological (or anemometric) and morphometric (or geometric) methods.

The prevalent micrometeorological method uses data of field observations of wind or turbulence for the roughness length and the zero plane displacement height computations based on the log-law:

$$\frac{\bar{u}(z)}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z - z_d}{z_0}\right)$$

where $\bar{u}(z)$ is the time averaged wind speed in z height, $u_*$ is the friction velocity and $\kappa$ is von Karman's constant (*Counihan,* 1975). For this equation we need wind speed data from at least one height above the surface therefore this method is unsuitable for roughness mapping in urban areas.

There are several known morphometric methods which are based on surface morphology data. The simple ones use only the average heights and density of the roughness elements in the cities (e.g. *Counihan,* 1975; *Bottema,* 1997). The sophisticated methods include the computation of the frontal area index, which combines the mean height, width and density of the roughness elements (*Grimmond and Oke,* 1999). The results of these methods mean more accurate approximations for the roughness parameters (e.g. *Lettau,* 1969; *Raupach,* 1992; *Macdonald et al.,* 1998).

The above-mentioned methods are based on regular building arrangement and there are only a few examples of their generalization. *Ratti at al.* (2006) calculate the $\lambda_P$, $z_H$, $\lambda_F$ and $z_0$ from urban digital elevation model (DEM) however their computation is applied for small sample areas. *Bottema and Mestayer* (1998) present a method for urban roughness mapping. This method is based on a cadastral database (vector-based building database) and the spatial basis of the computation is the rugoxel (roughness pixel). The applied $z_0$ and $z_d$ formulas are referring to these rugoxels and give average values.

### *2.1. Compution of the roughness length and the zero displacement height in irregular building groups*

The basis of the roughness length computations is in accord with the method of *Bottema and Mestayer* (1998). His basic equation was designed for regular building groups:

$$z_0 = (h - z_d)\exp\left(-\frac{\kappa}{\sqrt{0.5 \cdot C_{Dh} \cdot \lambda_F}}\right) \tag{2.1}$$

where $h$ is the volumetrically averaged building height, $z_d$ is the zero displacement height, $\kappa$ is von Karman's constant (0.4), $C_{Dh}$ is the isolated obstacle drag coefficient (0.8) and $\lambda_F$ is the frontal area density.

The next computation formula of the zero displacement height gives an opportunity to use *Equation 2.1* for irregular building groups (*Bottema and Mestayer,* 1998):

$$z_d = h \cdot (\lambda_P)^{0.6} \tag{2.2}$$

where $\lambda_P$ is the plan area density. With this equation we can give an approximate value for $z_d$ without taking the volume of the buildings and the recirculation zones into account.

For these equations we need some input parameters. *Fig. 2* shows these parameters for an irregular building group. The basis of the calculation of these input parameters is the building block; therefore the contiguous buildings were classified into blocks (*Fig. 2a*).

We divided the study area in polygon-shape areas (lot area) based on these blocks. Each polygon consists of the set of points closer to the central building block than to the other blocks. We defined the total surface or lot area ($A_T$) as the complete area of these polygons (*Fig. 2a*). The plan area of the roughness elements ($A_P$) is the sum of the surface areas of the buildings ($A_{P1}$, $A_{P2}$, $A_{P3}$, ..., $A_{Pn}$) are the areas of buildings. The plan area density is the ratio of the total plan area of the roughness elements and the total surface area ($\lambda_P = A_P / A_T$).

The computation of the volumetrically averaged building height needs the volumes ($V_1$, $V_2$, $V_3$, ..., $V_n$) and heights ($h_1$, $h_2$, $h_3$, ..., $h_n$) of each building (*Fig. 2a*) in each block:

$$h = \frac{\sum_{i=1}^{n} V_i \cdot h_i}{\sum_{i=1}^{n} V_i}$$

For the calculation of the frontal area density we have to compute the frontal area ($A_F$) of each building (*Fig. 2b*). This frontal area of a building block depends on the direction of the view (or direction of the airflow). In our calculations the frontal area density is defined as the ratio of the frontal area and the total surface area ($\lambda_F = A_F / A_T$).

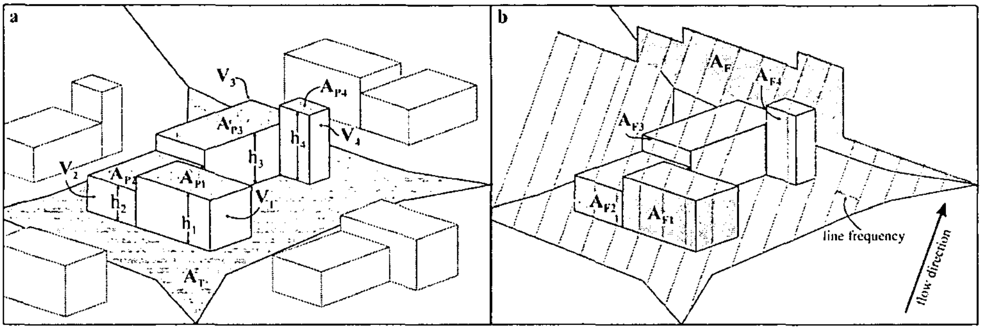


*Fig. 2* *(a)* Input parameters for the roughness calculation for an irregular building group and *(b)* frontal area calculation with the parallel lines in a given direction

### 2.2. Calculation of the porosity in the urban canopy layer

Porosity could be a useful roughness parameter in the UHIC modeling because it quantifies the ratio of open air volume in the canopy layer. By definition it is the ratio of the volume of the open air and the volume of the entire urban canopy layer (UCL) referring to the same area. There are two possible ways to compute this parameter. The first is less precise however easy to evaluate for urban areas, the second is much more accurate but the computation is rather time-consuming.

Porosity ($P_{h\text{-}const}$) evaluation with the first method is based on the input parameters of building volumes, total surface area (lot areas) and the height of the UCL ($h_{const}$) which is defined as a constant. This constant value is based on the analysis of the buildings' heights in the entire study area. The principle is that the number of buildings higher than the UCL height has to be significantly low in the entire area. So the equation of this type of porosity of a spatial unit (lot area) is the following:

$$P_{h-const} = \frac{A_T \cdot h_{const} - V}{A_T \cdot h_{const}} \tag{2.3}$$

where $V$ is sum of the building volumes located at the actual lot area.

The second method of porosity ($P_{h\text{-}var}$) computation is based on variable urban canopy layer heights by spatial units. For each spatial unit of the investigated area the height of the UCL ($h_{UCL}$) has to be computed. Based on these values the equation of this type of porosity of a spatial unit is the following:

$$P_{h-\mathrm{var}} = \frac{A_T \cdot h_{UCL} - V}{A_T \cdot h_{UCL}} \tag{2.4}$$

## 3. ROUGHNESS MAPPING IN THE URBAN AREA OF SZEGED

### *3.1. Study area and the building database*

Szeged (46°N, 20°E) is located in southeast Hungary, in the southern part of the Great Hungarian Plain at 79 m above sea level on a flat plain (*Fig. 3*). According to Trewartha's classification Szeged belongs to the climatic type D.1 (continental climate with longer warm season), similarly to the predominant part of the country (*Unger,* 1996). While the administrative area of Szeged is 281 km$^2$, the urbanized area is only around 30 km$^2$. The avenue-boulevard structure of the town was built to the axis of the river Tisza. Szeged is a medium-sized town and the number of the inhabitants is about 160,000.

In the earlier urban climate investigations the temperature measurements for identifying the UHI were taken in a 25,75 km$^2$ sized area of Szeged. Our study is partly based on the earlier results therefore we used the same study area (e.g. *Unger et al.,* 2000, 2001; *Bottyán and Unger,* 2003; *Unger,* 2006) (*Fig. 3*).

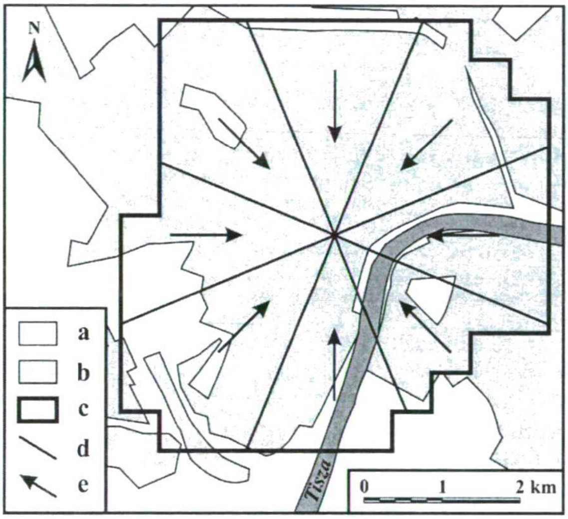


*Fig. 3* Study area and the calculation zones for the frontal area (*a:* rural area, *b:* urban area, *c:* border of the study area, *d:* border of the frontal area calculation zone, *e:* direction of the frontal area computation)

From earlier projects there is a 3D building database available for the study area. This data source is based on local municipality data on building footprints and the individual building heights were evaluated by photogrammetric methods. This means more than 22,000 individual buildings with their main parameters (footprint area, building height). The creation of the database is described in details in *Unger* (2006, 2007).

### *3.2. Details of the roughness calculations*

*Fig. 4* summarises the main steps of roughness mapping in the study area. Firstly, we have aggregated the buildings in the database to building blocks, similarly to the work of *Ratti et al.* (2006). That resulted in more than 11,000 blocks in the study area, each containing the interlocking buildings. Based on these building blocks the determination of the lot areas is achievable with ArcView 3.2 software by using the assign proximity function of the Spatial analyst module. All of the roughness parameter calculations were carried out for these lot area polygons (units) (*Fig. 5*).

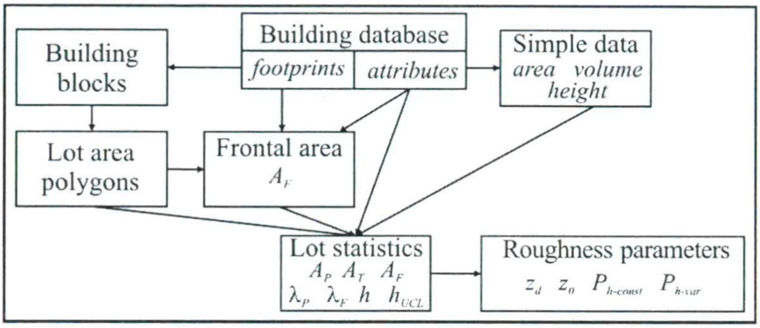


*Fig. 4* Schematic description for the roughness mapping procedure


*Fig. 5* As an example, some lot area polygons (units) in a part of the investigated area in Szeged (*a*: building footprints, *b*: building blocks, *c*: lot area polygons)

The values of some roughness parameters depend on the wind direction. The calculation methods of these parameters are also direction-dependent because of the application of the direction-dependent frontal area ($A_F$) as an input. Generally these roughness parameters are computed for several directions and the obtained results are averaged giving the final value (*Ratti et al.*, 2006). As our main objective is the mapping of the ventilation paths which have conducive effect on the heat island circulation, we evaluated these roughness parameters in radial directions within each calculation zones (see *Fig. 3*).

The frontal area calculation in ArcView is a more complex task than the calculation of the footprint area, the volume and other simple parameters. Therefore we have constructed a simple Avenue script for this calculation. Before the evaluation a shape file needs to be created, containing lines parallel with the given radial direction and covering each frontal area calculation zone (see *Fig. 2b* and *Fig. 3*). The distance between the neighboring lines is 5 m. The algorithm is searching for the highest building elevation in each lot using the line–building intersections for each line. Based on these elevation values and the line frequency (5 m) the frontal area is computable (see *Fig. 2b*).

With the frontal area calculation all of the input parameters for the $z_0$ and $z_d$ calculation become available (*Equations 2.1* and 2.2). The obtained values refer to the lot area polygons of the investigated area.

The porosity values are calculated with *Equations 2.3* and *2.4*. For the $P_{h\text{-}const}$ calculation we analyzed the heights of the buildings in the study area and defined $h_{const}$ ($P_{h\text{-}40}$) as 40 m. For the $P_{h\text{-}var}$ calculation we defined $h_{UCL}$ as the height of the highest building within a given lot area (its maximum is 63.4 m and its mean is 6.59 m on the study area).

## 4. SPATIAL DISTRIBUTIONS OF THE CALCULATED PARAMETERS AND THE POTENTIONAL VENTILATION PATHS

As a result of our calculations we have got the values of the roughness parameters referring to the plot area polygons. Based on this database we can analyze the spatial distributions of these parameters in order to find the potential ventilation paths.

*Fig. 6* shows the spatial distribution of $z_0$ as well as the supposed ventilation paths in the investigated area. We have located the ventilation paths with a method similar to the one used by *Matzarakis and Mayer* (1992). The analysis is based on this map only and we have not applied precise calculations with the $z_0$ and other values to find the locations of the ventilation paths.

We also examined the spatial distribution of the $P_{h\text{-}40}$ (*Fig. 7a*) and $P_{h\text{-}var}$ (*Fig. 7b*). Comparing the two figures we find that the spatial distribution of the first parameter is similar to the spatial distribution of the $z_0$. The shapes of the possible ventilation paths based on $P_{h\text{-}40}$ values in *Fig. 7a* (not shown) would be similar to the shapes on *Fig. 6*.

If we examine *Fig. 7b* we can identify new areas which can take a part in the city ventilation. For instance, on the east side of the town there is an area with high blocks of flats and large green areas between them. Because of this special built-up style this area can also be regarded as a potential ventilation path disregarding the relatively high roughness length values.

## 5. CONCLUSIONS

We have calculated the main roughness parameters in the study area. This calculation is based on a 3D building database and it is more detailed than those in other recent studies in this topic (e.g. *Bottema*, 1997; *Ratti et al.*, 2006). The calculation based on the lot area polygons is a new approach and according to our knowledge there are no similar examples in the literature.

Based on the spatial distribution of the calculated parameters we can locate the potential ventilation paths. These ventilation paths could take an important role in the development of the urban heat island circulation and as a result in the reduction of air pollution in the inner part of the city.

Based on our results we can give a list of the areas where the city government should have to consider the six advices of *Barlag and Kuttler* (1990) to keep the advantages of the ventilation paths considering the human comfort aspects of the urban climate.

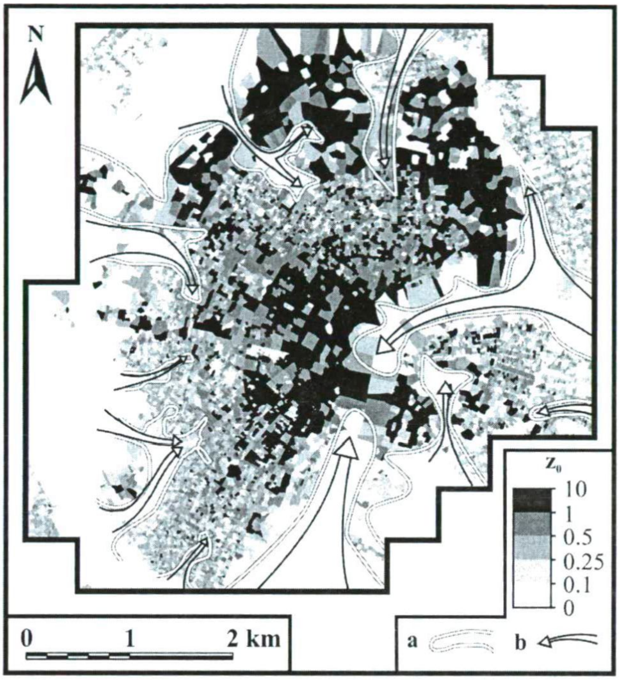


*Fig. 6* Spatial distribution of the roughness length ($z_0$) values and the supposed ventilation paths in the investigated area (*a:* border of a continuous area with $z_0$ values lower than 0.5, *b:* supposed ventilation path)

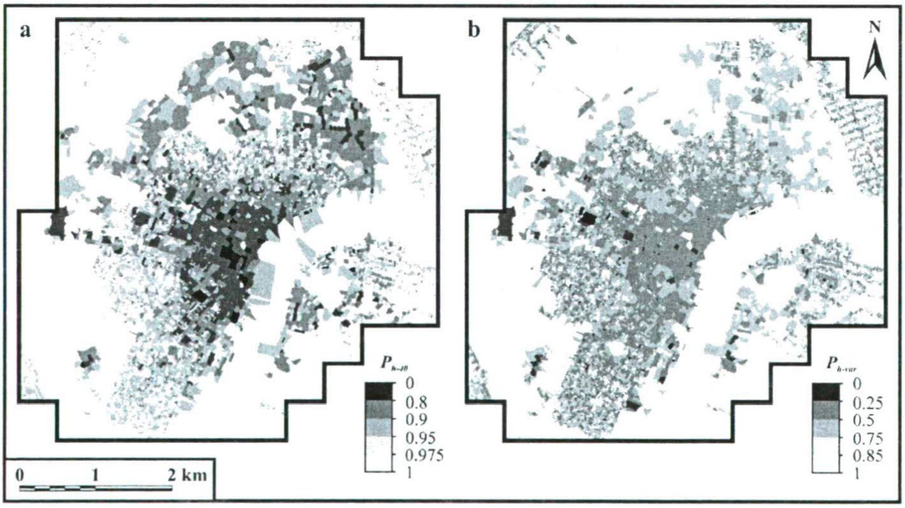


*Fig 7.* Spatial distribution of the porosity values in the investigated area (*a:* $P_{h\text{-}40}$, *b:* $P_{h\text{-}var}$)

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## REFERENCES

*Barlag, A.B. and Kuttler, W.*, 1990: The significance of country breezes for urban planning. *Energy and Buildings 15-16*, 291-297.
*Bottema, M.*, 1997: Urban roughness modelling in relation to pollutant dispersion. *Atmos. Environ. 31*, 3059-3075.
*Bottema, M. and Mestayer, P.G.*, 1998: Urban roughness mapping – validation techniques and some first results. *J. Wind Engineering and Industrial Aerodynamics 74-76*, 163-173.
*Bottyán, Z. and Unger, J.*, 2003: A multiple linear statistical model for estimating mean maximum urban heat island. *Theor. and Appl. Climatology 75*, 233-243.
*Counihan, J.*, 1975: Adiabatic atmospheric boundary layers: A review and analysis of data from the period 1880-1972. *Atmos. Environ. 9*, 871-905.
*Eliasson, I. and Holmer, B.*, 1990: Urban heat island circulation in Göteborg, Sweden. *Theoretical and Applied Climatology 42*, 187-196.
*Grimmond, C.S.B. and Oke, T.R.*, 1999: Aerodynamic properites of urban areas derived from analysis of surface form. *J. Appl. Meteorol. 34*, 1262-1292.
*Lettau, H.*, 1969: Note on aerodynamic roughness-parameter estimation on the basis of roughness-element description. *Appl. Meteorol. 8*, 828-832.
*Macdonald, R.W., Griffiths, R.F. and Hall, D.J.*, 1998: An improved method for estimation of surface roughness of obstacle arrays. *Atmos. Environ. 32*, 1857-1864.
*Matzarakis, A. and Mayer, H.*, 1992: Mapping of urban air paths for planning in Munchen. Wiss Ber Inst. Meteorol. *Klimaforsch. Univ. Karlsruhe 16*, 13-22.
*Oke, T.R.*, 1987: *Boundary layer climates*, Routledge, London and New York. 435 p.
*Ratti, C., Di Sabatino, S. and Bitter, R.*, 2006: Urban texture analysis with image processing techniques: wind and dispersion. *Theor. and Appl. Climatol. 84*, 77-99.
*Raupach, M.R.*, 1992: Drag and drag partition on rough surfaces. *Bound. Lay. Meteor. 60*, 375-395.
*Unger, J.*, 1996: Heat island intensity with different meteorological conditions in a medium-sized town: Szeged, Hungary. *Theor. and Appl. Climatol. 54*, 147-151.
*Unger, J.*, 2006: Modelling of the annual mean maximum urban heat island with the application of 2 and 3D surface parameters. *Clim. Res. 30*, 215-226.
*Unger, J.*, 2007: Connection between urban heat island and sky view factor approximated by a software tool on a 3D urban database. *Int. J. Environment and Pollution* (in press)
*Unger, J., Bottyán, Z., Sümeghy, Z. and Gulyás, Á.*, 2000: Urban heat island development affected by urban surface factors. *Időjárás 104*, 253-268.
*Unger, J., Sümeghy, Z., Gulyás, Á., Bottyán, Z. and Mucsi, L.*, 2001: Land-use and meteorological aspects of the urban heat island. *Meteorol. Applications 8*, 189-194.
*Vukovich, M.F.*, 1971: Theoretical analysis of the effect of mean wind and stability on a heat island circulation characteristic of an urban complex. *Monthly Weather Review 99*, 919-926.